Low Cost, Metal Hydride Hydrogen Storage System for Forklift Applications

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Joint Venture Partners*: *Select Engineering Services (SES)* and *Hawaii Hydrogen Carriers, LLC (HHC)

US DOE Annual Merit Review Meeting

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Project ID #:ST 095

Overview

Timeline

- Phase I: July 2010 - April 2011
  - 100% Complete
- Phase II: Proposed

Budget

- Phase I: $115,900
  - US DOE: $99,900
  - Hawaii High Technology Development Corp. (HTDC) $16,000
- Phase II: Proposed

Barriers

- System Volume/H2 Capacity
- System Cost
- Charging/Discharge Rates
- Durability/Operability
- Materials of Construction
- Thermal Management

Partners

- Sandia National Laboratories
  - Design and Testing
- Plug Power
  - Fuel Cell and Integration Supplier

Relevance

Objective/Main focus: Prove Metal Hydride Solid State (*MHSS*) based systems provide a cost competitive favorable H2 storage option for zero-emission low speed materials handling vehicles (*e.g., forklifts*) for industrial applications. The subject design reduces costs over competitive systems as shown below:

$	Batteries	High Pressure (HP) H2
Up-Front	• Requires chargers & battery exchangers (*for 24/7 units*)	• HP refueling infrastructure
Lifecycle	• Approx. ½ lifespan of PEMFC • Lost productivity as batteries loose charge/age • Lost productivity as dramatically increased charge time (*10 min vs. up to 16 hrs*) • Floor space for chargers/changers • Safety measures for corrosive batteries	• Compression energy is required • Fuel storage capacity is 35% less than MHSS • Floor space for refueling infrastructure • Safety measures, liability, and hazards related to HP H2 (*~5000 vs. ~650 psi for MHSS*)

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Relevance (cont'd)

Other Project Objectives Proven in Phase I

Performance Barriers	Phase I
Storage Capacity	• Optimized to 35% over 5000 psi system
Materials of Construction	• Readily available/inexpensive 316 stainless steel
Thermal Management	• On-board cooling modeled for H2 absorption • Appropriate alloy obtained/tested for suitable H2 desorption at PEMFC operating temperatures/pressures
Durability/Operability	• Material can be "renewed" indefinitely to original H2 storage capacity • Easily integrated with PEMFC
Path to Commercialization	• Shown using market research/cost/competitive analysis • Strengthened via existing relationships with PEMFC and Forklift OEM's

Approach

- Solid-state H_2 storage technology based on metal hydrides has been used in many H_2 powered demonstration vehicles over the past 20 years. AB_5 alloys have also been extensively studied. Thus, the level of R&D already completed lends itself to the immediate next step of finding lower cost components and manufacturing techniques that allow widespread adoption of this technology.
- Prototype systems utilizing AB_5 alloys have consistently met performance targets in low speed materials handling vehicles.
- Commercial viability has awaited a significant reduction in the cost of AB_5 based H_2 storage systems.

Approach (cont'd)

- The heavy weight of storage systems based on traditional metal hydrides is typically considered to be a disadvantage compared to ultra high-pressure tanks. However, the weight of the hydride is actually an **advantage** in this application as the current PEMFC systems require large cast iron frames to provide counterbalance for the forklift while in operation. These frames can be minimized and the increased volume used for hydrogen storage as the weight of the metal hydride material serves as forklift ballast.

- The objectives of the **SBIR Phase I** project were to design a metal hydride based H2 storage system that would: 1) operate as per specifications in PEMFC powered forklift applications **and** 2) be cost competitive with compressed gaseous storage system.

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Approach (cont'd)

Phase I focused on demonstration of the following specific system capabilities:

- A storage capacity substantially greater than HP H2 fueling systems
- Specific energy and energy density acceptable for the forklift application
- Operating temperature and pressure function within parameters that allow ambient temperature start-up and continual operation of the PEMFC
- Hydrogen delivery rate matching that required by the PEMFC at maximum operating output
- Achievable recharge times without the need of an off-board cooling infrastructure
- A projected MHSS H2 fuel system service life equal to *(or greater than)* that of the HP fuel system
- Transient response time of the system is within an acceptable range

Approach (cont'd)

Proposed Phase II effort:

- Prove Phase I system modeling via testing at subcomponent level
- Optimize and finalize design of the MHSS fuel system for PEMFC powered forklift applications
- Test, Qualify, and Certify the MHSS fuel system design in collaboration with PEMFC and/or forklift OEMs
- Fabricate MHSS PEMFC powered forklift; deploy and test in an operational environment, adjust design, and initiate commercial sales and manufacture

Technical Accomplishments and Progress

Market Research to Determine Viable PEMFC System Manufacturers

Due to the limited size of the U.S. PEMFC industry *(specifically PEMFC system providers to forklift OEM's)*, only three companies were analyzed for the suitability of their PEMFC as an appropriate interface to our MHSS fuel system. The PEMFC selected for Phase II design and implementation was the ***Plug Power GD-170***. In addition to Plug Power's favorable responsiveness and supply of operational data, their PEMFC was specifically selected since it proved ideal for integration with our large scale MHSS fuel system design.

Technical Accomplishments and Progress (cont'd)

Specific aspects resulting in the selection of the Plug Power GD-170 included:

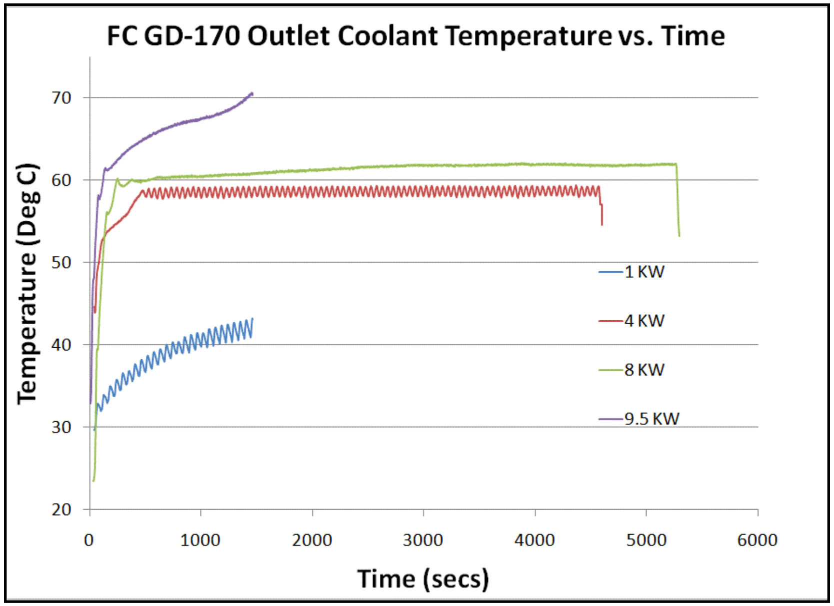
- Capability to achieve documented performance requirements including suitable operational temperature range, power generation, durability, and manufacturing cost
- Prior successful integration within a viable PEMFC forklift platform
- Application of a proven, reliable Ballard PEMFC stack
- The existence of a H2 cooler on the H2 inlet line
- Existing inbuilt algorithm that controls coolant temperature via comparing inlet/outlet temperatures sensor values and varying pump/fan speed
- The coolant pump used provides high flow with spare capacity

Technical Accomplishments and Progress (cont'd)

Detailed PEMFC Analysis

PEMFC performance parameters were defined and OEM PEMFC performance data was analyzed to determine which system best matched documented requirements. Specific attention was given to H2 consumption, pressure requirements, operating temperature, pump/fan flow-rates and heat dissipation requirements throughout the PEMFC's operating range. Extensive numerical analysis was conducted using the down-selected PEMFC system's operational data to assist in determining a suitable AB5 alloy for the PEMFC and to facilitate scoping of the required reservoir design characteristics. Data provided also included storage system size/performance and "casing" dimensions/weights; along with other key system attributes such as refill times, and control system functionality *(including a detailed list of built-in sensors)*.

Technical Accomplishments and Progress (cont'd)



The HHC/SES MHSS fuel system was designed to provide the selected GD-170 PEMFC with adequate pressure during start-up and at maximum operating temperatures

Extensive mounting casting required within the HP PEMFC forklift design is virtually eliminated by our MHSS PEMFC design.

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Technical Accomplishments and Progress (cont'd)

AB5 Alloy Research and Selection

Extensive analysis resulted in the selection of **Hy-Stor 208, $MmNi_{4.5}Al_{0.5}$**

- Meets the requirement of sufficient pressure for start-up at above 5 ^{o}C regardless of tank level; alleviating the previous requirement for a start-up "buffer" H2 tank
- Provides ~300 psi max. H2 pressure at PEMFC T_{max} of 75 ^{o}C.
- Sufficient storage capacity of 1.2 weight %
- H2 desorption rate will be sufficient for the operating temperatures and pressures of the selected PEMFC
- The addition of Aluminum induces well documented resistance to "disproportionation" (*and can be "renewed" to original capacity*)
- Cost effective and readily available

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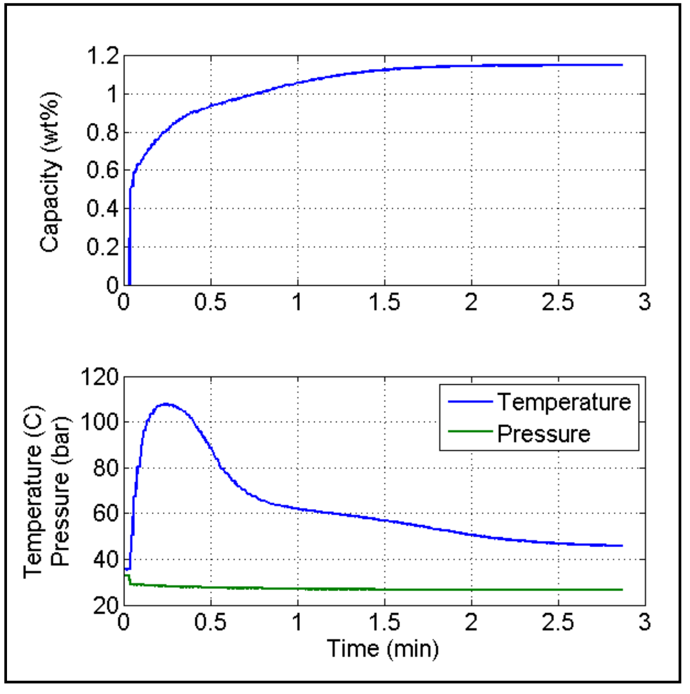
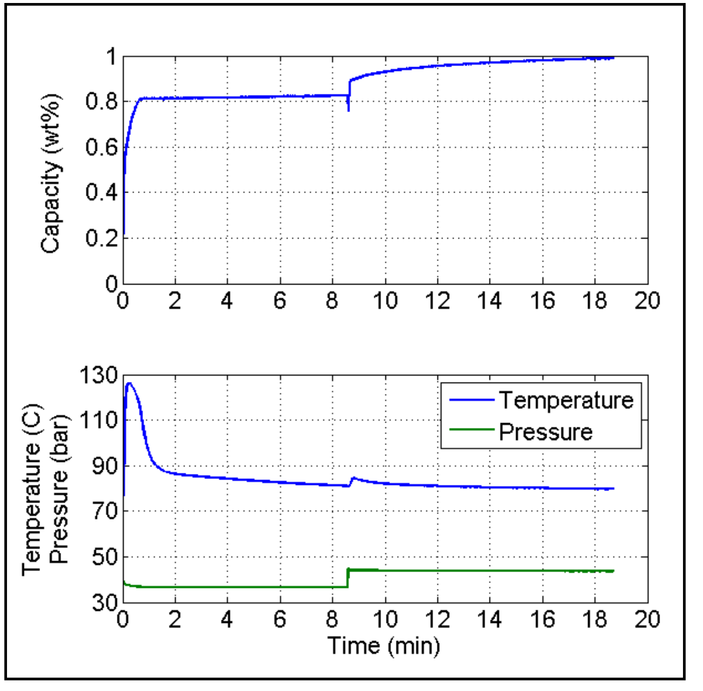
Technical Accomplishments and Progress (cont'd)





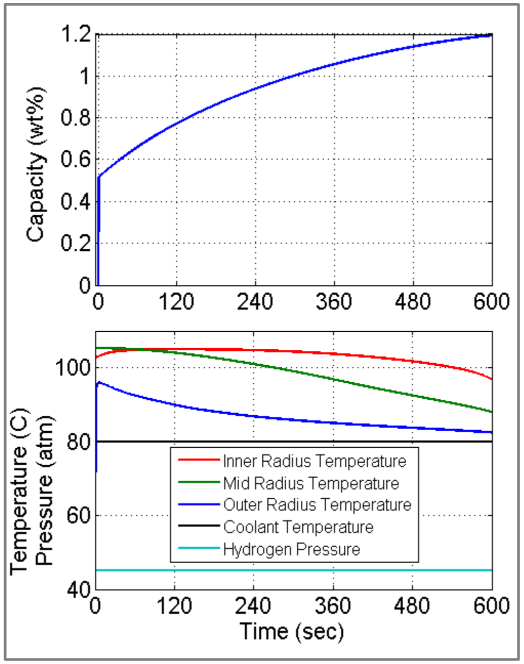
Absorption profiles for Hy-Stor 208. $MmAl_{4.5}Ni_{0.5}$ at various pressures. Demonstration of rapid kinetics and acceptable H2 capacity.

Technical Accomplishments and Progress (cont'd)

Reservoir Engineering Design

Various design concepts were analyzed. A tube and shell heat exchanger design was selected for mass and volume efficiency, H2 refill and delivery performance, and cost.

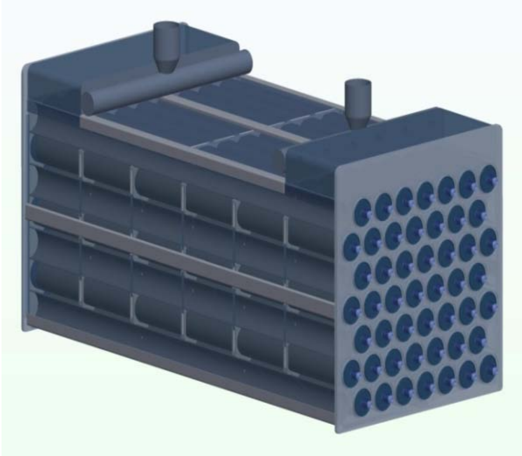
- Refueling rate limiting design requirement
- Effective thermal conductivity can be achieved with 4% expanded natural graphite as heat treansfer enhancement mechanism (*1 g/cm³ packing density*)
- Shell designed to withstand maximum pressure of the cooling fluid
- Pressure drop calculated at an acceptable 0.23 psi. (~*8 psi spare pump capacity*)

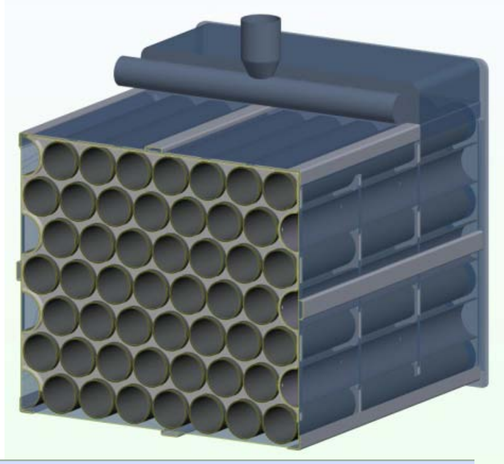


Refueling Simulation Results Showing the Full 1.2 weight % of H2 Absorbed in 10 min.

Technical Accomplishments and Progress (cont'd)

- Optimum design is a staggered array of 49 Hy-Stor 208 containing tubes (*3.5 g/cm^3 packing density*)
- Staggered array used to maximize the number of rows/columns that can fit in the given volume and improve heat transfer
- Spacing between tubes kept to a minimum for increased heat transfer and improved volumetric efficiency
- Baffles are used to alternate fluid flow
- Tubes contain 2 um porous separators to account for Hy-Stor 208 "decrepitation" (*initially 20-150 mesh*)
- **2.76 kg of H2** is stored within the targeted design volume which is absorbed in 10 min., using 49 x 2 O.D. (*0.065 wall*) stainless steel tubes
- Designed to ASME codes and standards





Technical Accomplishments and Progress (cont'd)

Manufacturing, Cost, and Commercialization Analysis

- Extensive market research conducted to locate the most cost effective components and alloy for use in the MHSS fuel system
- The total cost of all components in the system; including Hy-Stor 208 alloy, porous baffles and 316 stainless steel construction material and tubing; is estimated at less than our $15,000 target
- The design was optimized for low cost manufacturability (*less than $5,000*)
- Extensive market analysis and OEM/end user surveys were completed highlighting a vastly favorable value proposition over competing technologies (*Battery and HP PEMFC systems*)
- Based on conservative sales estimates, a financial and technical development path to commercialization was mapped

Collaborations

- Sandia National Laboratory

Hydrogen and Combustion Technology Department

(*T. Johnson and D. Dedrick)*

- Modeling, design & testing
- Total: 20%

- Plug Power

System Engineering/Fuel Cell Program Departments

(*D. Skidmore and B. Bestvater)*

- PEMFC supplier, design, integration support
- Total: 15%

Presently in discussions with Forklift OEM's, Crown and Raymond.

Future Work

Proposed Phase II Activities

- Utilize proven System Engineering Tools to optimize design of the MHSS fuel system for GD-170 PEMFC powered forklift applications
- Test, Qualify and Certify the MHSS fuel system design
- Conduct final fabrication and update, followed by operational testing of the MHSS fuel system within an integrated systems environment (*site operation in typical duty cycle*)

FY11 Summary

- **Relevance:** Demonstrated cost advantage over Battery and HP PEMFC systems with acceptable storage capacity, materials of construction, thermal management, durability/operability, and path to commercialization
- **Approach:** Provided background on application with practical advantages of system within acceptable operating parameters. Outlined plan to build, certify, and test market ready system
- **Technical Accomplishments and Progress:** Sourced and tested suitable alloy. Completed system design and demonstrated suitability for integration to PEMFC powered forklift platform
- **Technology Transfer/Collaborations:** Developed ongoing strong partnerships with Sandia National Laboratory and Plug Power. Entered into extremely promising discussions with Crown and Raymond Corporations
- **Proposed Future Research:** Optimize, test, qualify, and certify system

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